An Assessment of Molten Metal Detachment Hazards for Electron Beam Welding in the Space Environment: Analysis and Test Results

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AN ASSESSMENT OF MOLTEN METAL DETACHMENT HAZARDS FOR ELECTRON BEAM WELDING IN THE SPACE ENVIRONMENT: ANALYSIS AND TEST RESULTS

I. INTRODUCTION: WHY THIS STUDY WAS UNDERTAKEN

This study was undertaken in order to ensure that no hazard would exist from impingement of hot molten metal particle detachments upon an astronaut's space suit during extravehicular electron beam welding exercises in the space environment. The study addresses the needs of current and future space exploration efforts.

Emission of molten metal detachments is not uncommon for a wide variety of terrestrial welding processes including electron beam welding. Terrestrial electron beam welding is carried out in an enclosed vacuum chamber. In the space environment such emissions could present a serious hazard to the life of an astronaut if they were to burn through the fabric of the extravehicular mobility unit (EMU).

By "molten metal detachment"[1] is meant the separation of a particle of molten metal from the welded or cut surface or from the weld wire by dynamic loading effects (g-forces or impulse loads). Cases of molten metal separation from weld/cut sample or wire driven by local vaporization are treated elsewhere under the category of "sparking."

Thus, under the heading of molten metal detachment comes the dropout of the weld pool under the force of gravity in terrestrial situations. Given g-forces on the order of 0.001 times Earth's surface gravity, for example, in the Space Shuttle cargo bay at low-Earth orbit (LEO), a massive detachment of this sort seems unlikely.

Another way of producing a molten metal detachment is an impulse (i.e., a bump) to the weld sample or wire. Possibly a large drop of molten metal could accumulate on the end of the weld wire and be shaken off. A sample plate with molten metal pool or droplets on one side of a cut surface might be struck so as to release a drop of molten metal. The weld wire might be snapped out of the weld pool so as to entrain and release a molten metal drop.

In general, weld metal detachments are conceived as bigger and moving at lower velocity than sparks. Liquid metal detachments are considered more of a threat than sparks with regard to the higher energy content of the detachments, but it is anticipated that they will also be less likely to occur and easier to avoid if they do occur.

It has been deemed a necessary precaution to initiate a study of molten metal detachment before carrying out any space welding experiment, notwithstanding Ukrainian space welding experience which suggests that the potential hazards of welding in space are negligible.

II. ANALYSIS

The first part of this study consists of an analysis with the objective of assessing potential molten metal detachment hazards during electron beam welding in the space environment. In this analysis potential molten metal detachment mechanisms are conceptualized and modeled. The modeling is then followed by appropriate tests to confirm analytical conclusions and to answer questions not resolvable by analysis alone.

A. Molten Metal Detachment

1. Gravitational Considerations

Surface tension holds molten metal drops in place against the action of terrestrial gravitational forces. Referring to figure 1 let us consider the detachment of a molten metal drop attached to the end of a wire of radius a.
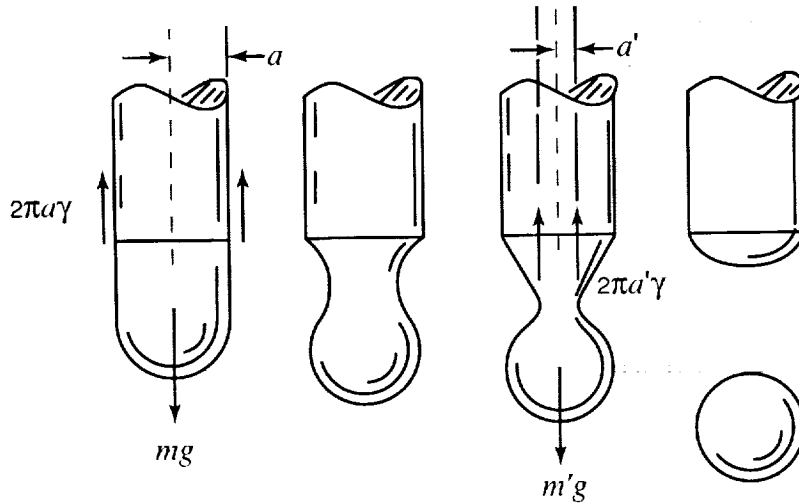
Figure 1. Gravitational detachment of a drop from the end of a wire.

When the gravitational force mg on the drop, where m is the mass of the drop and g the acceleration of gravity, exceeds the maximum surface tension force attaching the drop to the wire, $2\pi a \gamma$ in the case depicted, γ being the surface tension of the molten metal, the drop becomes unstable. At the onset of instability, the drop surface develops a waist of radius a' that begins to contract. The surface tension force on the mass m' below the waist drops below $m'g$, and the mass m' begins to accelerate under force $m'g - 2\pi a'\gamma$.

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Given a drop of diameter d of metal with density ρ subjected to a gravitational field of acceleration g held to a surface at a circle of about the same diameter, the minimal drop detachment diameter is:

$$d \geq \sqrt{\frac{6\gamma}{\rho g}} \; . \tag{1}$$

Under terrestrial conditions equation (1) yields a detachment size of the order of 1 cm for typical metal values. For example, for iron $\rho = 7.87$ g/cm^3 and γ is in the neighborhood of 1,000 dyn/cm, which, with $g=980.6$ cm/sec^2, yields 0.9 cm. For aluminum, with ρ and γ approximately 2.70 g/cm^3 and 900 dyn/cm, the anticipated detachment size is somewhat bigger, 1.4 cm. These values are of the same order of magnitude as the typical puddle size, and, because of this, one would expect to encounter situations where the puddle drops out. Indeed such situations are occasionally encountered in terrestrial welding operations. Deep full-penetration welds, particularly in dense metals, require backing bars to hold the weld puddle in.

On orbit, however, with the highest anticipated g-loading of 0.001 times terrestrial gravity, the anticipated detachment size rises by a factor of 31.6. This is much larger than any anticipated puddle size or drop size produced on the specimen during welding. Hence, gravitational detachments are not anticipated for on-orbit welding.

2. Impulse Considerations

If gravitational acceleration will not detach molten metal, what about an impulse caused by a bump or shock of some kind? A drop of mass Δm attached to the edge of a plate is shown in figure 2.
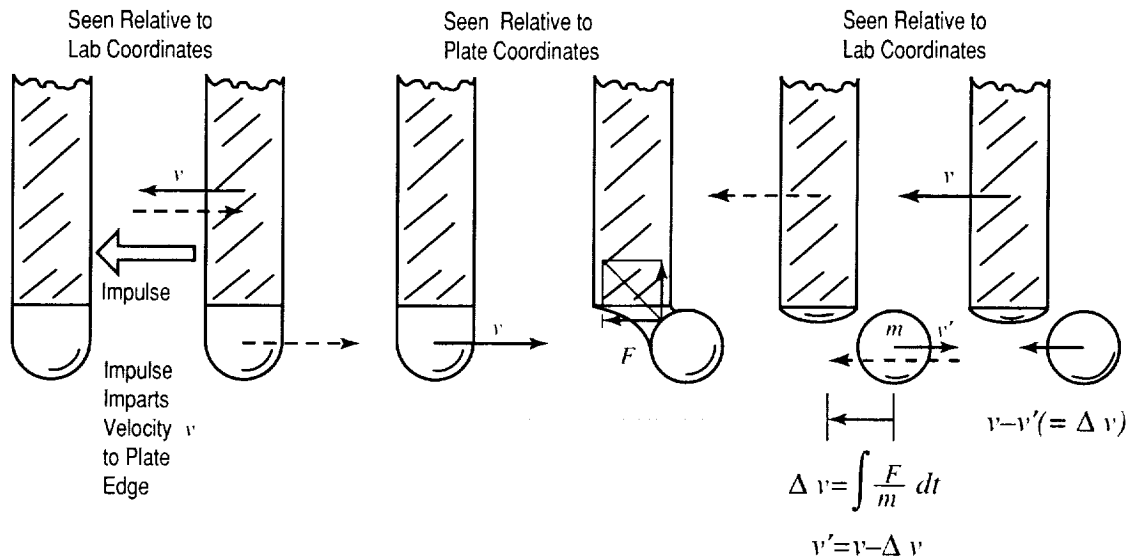

Figure 2. Impulse detachment of a molten metal drop from a plate edge.

Suppose that the plate receives an impulse that leaves it with a velocity v. From coordinates fixed on the plate the drop appears to have relative velocity $-v$. The drop, not yet being detached, is restrained in its movement away from the plate by the force of surface tension. The drop kinetic energy relative to the plate, which starts at $1/2\ \Delta mv^2$, is reduced by the increment of new surface energy $\gamma\Delta A$, where γ is the surface tension and ΔA is the surface area increase, created as the drop stretches the surface connecting it to the plate. If $1/2\ \Delta mv^2$ is enough to supply all the potential energy $\gamma\Delta A$ required for detachment, then the drop detaches. The minimum velocity required to detach a drop of diameter d can be obtained by equating the two energies:

$$v \geq \sqrt{\frac{12\gamma\Delta A}{\pi\rho d^3}}\ ,\qquad(2)$$

where ρ is the density of the drop material. Further, suppose that the new surface required for separation is on the order of twice that for a right circular cone with base equal to d and height equal to $0.866d$ such that the surface area comes out to be the convenient expression $\pi/2d^2$. In this way a rough approximation to the velocity needed to knock off a drop of a certain known size can be arrived at:

$$v \geq \sqrt{\frac{12\gamma}{\rho d}}\ .\qquad(3)$$

To detach iron or aluminum drops of 2-mm-diameter velocities of 87 cm/sec or 141 cm/sec, respectively, would be required according to equation (3). Detachment of drops 1 cm in diameter would require 39 or 63 cm/sec, respectively. (Note that for water with its surface tension of only about 70 dyn/cm and density of 1 g/cm^3 a velocity of 65 cm/sec is required to detach a 2-mm drop.)

So what kind of a blow would be necessary to raise the velocity of the weld specimen to somewhere in the vicinity of 100 cm/sec? Suppose that the effective mass of the total specimen is m and that a striker of mass M strikes it at velocity V. After the collision the striker is left with velocity $V - \Delta V$ and the specimen has acquired velocity v:

$$v = \left(\frac{1+e}{1+\frac{m}{M}}\right)V\ ,\qquad(4)$$

where e is the "coefficient of restitution," the ratio of the difference in velocity between the colliding bodies after and before the collision. If the collision is elastic, the bodies rebound from one another such that e is one. If the bodies stick upon collision, e is zero.

If the specimen is mounted rigidly in a very heavy fixture so that the effective specimen mass m far exceeds any conceivable striker mass M, then the specimen cannot acquire a sufficient velocity for drop detachment. (Elastic oscillatory waves that occur even in heavy structures subject to shocks have to

have a sufficient amplitude to produce the necessary drop distortion for detachment if they are to be responsible for drop detachment. It is presumed here that they do not.)

For argument's sake, suppose that the specimens are mounted flexibly so that their effective mass is of the same order of magnitude as an astronaut's hand. Further suppose that if an astronaut strikes a specimen, the coefficient of restitution is unity. Then $v = V$, and the specimen takes on the velocity with which it is struck. Under these (ultraconservative) suppositions, if an astronaut were to strike a weld specimen bearing a molten metal volume equivalent to a drop on the order of 2 mm in diameter with a hand moving at 100 cm/sec, a detachment might occur. It is not hard to imagine a hand covering a meter distance in a second; certainly 100 cm/sec is easily attainable. However, rigidly mounted specimens would more likely have an effective mass at least an order of magnitude greater than that of an astronaut's hand. In such a case, an astronaut would have to strike with 550 cm/sec.

Events of the sort described resulting in putative liquid metal detachment are deemed highly unlikely. The above analysis requires confirmation, however. A point mass pendulum striker raised on the order of 5 cm acquires the critical 100 cm/sec velocity ($v^2 = 2gh$, where h is the height of the pendulum and $g = 980.6$ cm/sec^2). Plans were made, therefore, to acquire data on the energy required to knock drops off various weld specimens (held in a less rigid fixture so that m/M would not be too high) under various welding and cutting conditions. For this purpose a "carillon" apparatus is shown schematically in figure 3, consisting of four pendulum strikers, each of several pounds weight with a length of ~ 1 1/2 ft. The strikers were released by switching on an electric motor to rotate a pin holding wires retaining the strikers at desired heights. The specimens were mounted on a hinged plate for minimizing effective mass with the option to fasten it down so as to raise its effective mass.
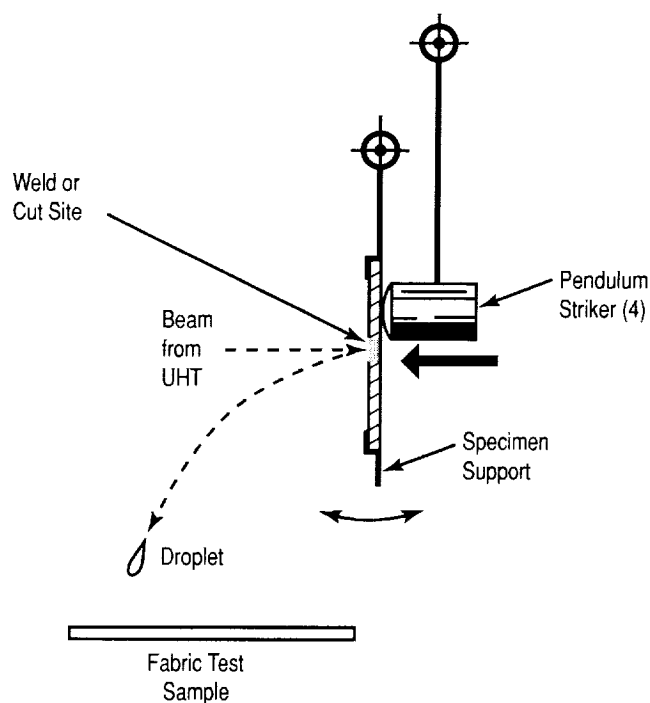

Figure 3. "Carillon" apparatus for impulse detachment of molten metal droplets.

Because the beaded droplets that form at the edge of a cut as the molten pool separates are all driven by gravity to the bottom of the cut as shown in figure 4 under terrestrial conditions, detached drops are caught again on the lower edge of the cut on the back side of the sample plate.
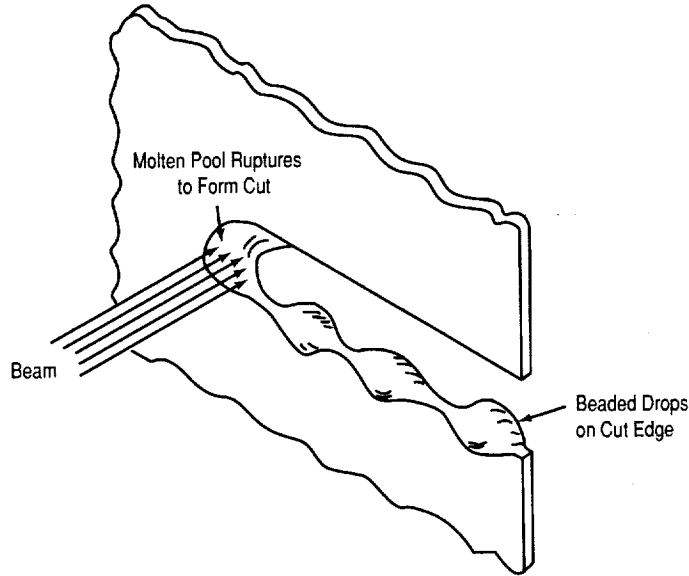

Figure 4. Beaded drops on the bottom edge of a cut under conditions of terrestrial gravity.

Forward-moving detachments are more easily obtained in a terrestrial environment from the unruptured weld pool of a full penetration weld rather than from the ruptured weld pool of a cut. Figure 5 shows schematically how the plug of molten metal comprising a full penetration weld pool is accelerated to velocity Δv when the plate surrounding it is given a velocity v by impulse I. If the detached metal clears the bottom edge of the hole left in the plate, a detached drop emerges from the front of the plate. The contraction of a large cylindrical puddle into a sphere due to surface tension should help the drop clear the hole edge. If too high a velocity v is given to the plate, the forces on the liquid metal, limited to surface tension forces and no more, have no time to apply a substantial impulse; Δv approaches zero, and the drop falls behind the plate and does not emerge.

A schematic of the "carillon" apparatus is also shown in figure 5. For purposes of analysis, the weld specimen plate and its mounting is taken to be a uniform pendulum of length L and mass m. The striker falls a distance h and strikes the specimen at distance L_R from its pivot. The weld pool of mass Δm is located at distance x from the specimen pivot. Both weld pool and plate are taken to have thickness w. For a detachment, the initial kinetic energy of the weld pool $1/2\ \Delta m v^2$ with respect to the plate has to exceed the energy $\gamma \Delta A$ to form the extra surface ΔA required for the detachment of the pool.

Thus, for a detachment to occur:

$$\frac{\frac{1}{2}\Delta m v^2}{\gamma \Delta A} \geq 1 \ . \tag{5}$$

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Taking Δm approximately equal to $\rho \pi r^2 w$ and ΔA approximately equal to $2(2\pi r w)$ and estimating v for the collision in the manner of equation (3) yields an approximate condition for drop detachment:

$$\frac{\rho g h r}{4\gamma}\left(\frac{x}{L_R}\right)^2\left[\frac{1+e}{1+\frac{1}{3}\left(\frac{L}{L_R}\right)^2\frac{m}{M}}\right]^2 \geq 1 \ . \tag{6}$$

Note that as far as the weld itself goes, the factors that determine the tendency for liquid metal detachment come together in the fraction $\rho r/\gamma$. Thus, according to the above, the tendency to detachment is directly proportional to pool radius and metal density and inversely proportional to the surface tension of the liquid metal.

A fabric sample being concurrently tested for the damage effect of molten metal droplets was placed to catch the falling detached drops. Measurements of the mass and residual velocity of the drop could be made by weighing the solidified drop and measuring how far out from the impact point ($x = vt$) the drop had moved during its fall of length s ($s = 1/2\ gt^2$).
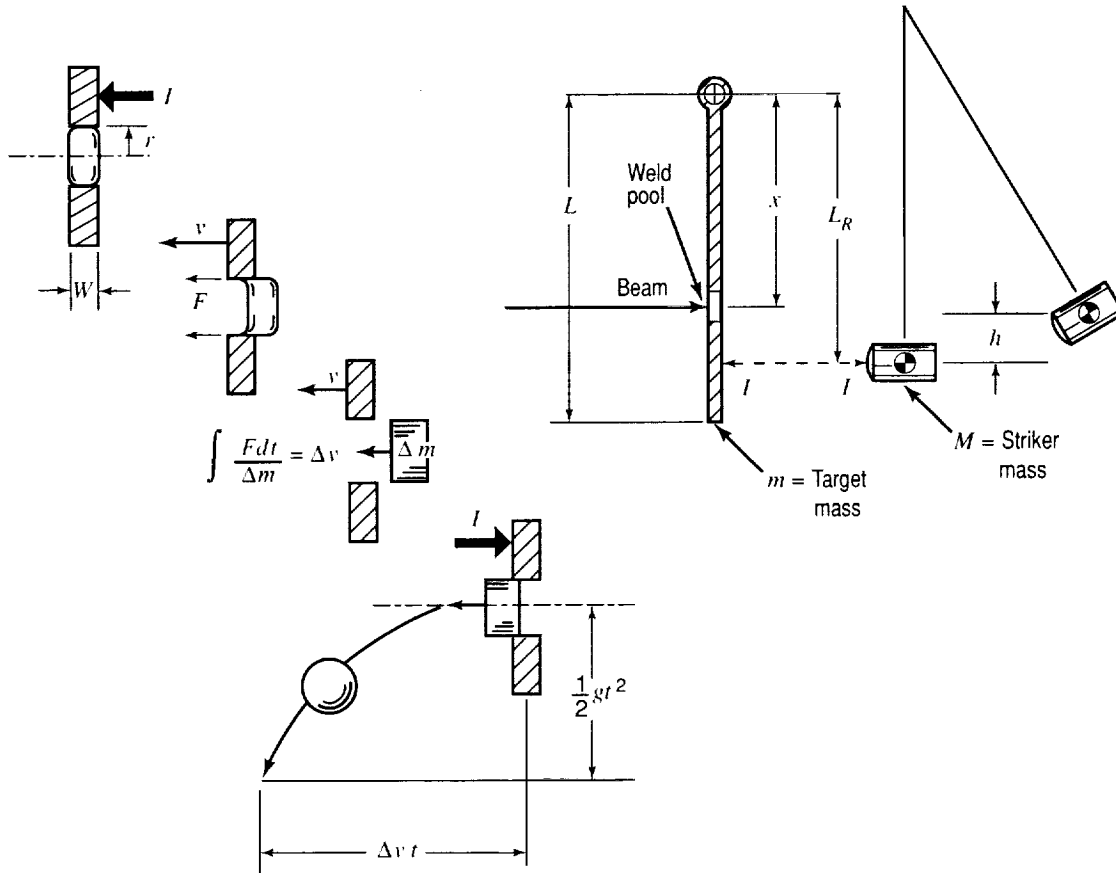

Figure 5. Schematic detachment of full penetration weld pool and analytical schematic of "carillon" detachment apparatus.

It should be noted that for the drop to move toward the astronaut the impulse must also be directed toward the astronaut. Thus, in the very unlikely event that an astronaut should detach a drop by striking the specimen, the drop would be expected to move away from, rather than towards, the EMU.

3. Vaporization Reaction

The impingement of the electron beam itself exerts a force that should be considered as a possible cause of molten metal detachment. This force, which results from the reaction of evaporating metal constituents on the beam impingement surface, is felt as a push on the order of the vapor pressure under the beam times the area of the beam impingement.

Vapor pressure is a sensitive function of surface temperature. Metal vaporization from weld pool surfaces has been studied to a point where some very crude estimates of such pressures are feasible.[2] However, beam impingement on a drop may result in higher temperatures and evaporation levels than for a weld pool if the metal pathways for dissipation of heat are narrower for the drop.

Suppose that the pressure is on the order of 0.01 atmosphere, or 10,000 dyn/cm^2, over an effective area of a square millimeter. The force exerted would be on the order of 100 dyn. A representational surface tension of 10^3 dyn/cm would require a length of ~ 1 mm to resist such a force if the force could be exerted so as to oppose the attachment forces of the drop, but the circumference provides 3.5 mm. Hence the metal should not be forced out. It is anticipated, however, that the vapor reaction force would rather push into the attached drop and clear a channel, a vapor cavity, as in high-power density electron beam welding.

In fact, since the beam power density from the Universal Hand Tool (UHT) has been attenuated so as to avoid formation of a vapor cavity, the mean pressure p within a given radius r must exert a force $p\pi r^2$ less than the balancing surface tension force $2\pi r\gamma$. Hence, the mean evaporation pressure within radius r must be less than $2\gamma/r$. Given a representational surface tension of 1,000 dyn/cm, the pressure on a 1-mm-diameter circle must be less than 40,000 dyn/cm^2, or 0.04 atmospheres, to avoid a vapor cavity. Therefore, the force on the 1-mm-diameter circle must be less than 314 dyn. Smaller drops, lacking the circumference for so large a surface tension force, also lack the area to absorb the whole beam and, hence, are also unmoved by evaporation forces.

Thus, it is not anticipated that the steady beam force should detach molten metal. What about transient conditions? In a worst-case scenario suppose that the beam suddenly impinges on a pool of molten metal at the vaporization temperature. The beam power minus the power leakage conducted away from the pool and the latent heat of evaporation of the metal imparts kinetic energy to the evaporated metal atoms. For a cylindrical pool of radius r, where the temperature at the pool edge is the melting temperature, an approximate energy balance can be written:

$$\frac{1}{2}dm\left(v_x^2 + v_y^2 + v_z^2\right) \approx \left(IV - \frac{2\pi kw\left(T_m - T_o\right)}{ln\left(\frac{r}{r_o}\right)}\right)dt - L_f dm \ , \tag{7}$$

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where dm = increment of evaporated mass

  v_x = velocity in x-direction
  v_y = velocity in y-direction
  v_z = velocity in z-direction
  I = beam current
  V = beam voltage
  k = thermal conductivity of weld metal
  w = thickness of plate
  T_m = pool melting temperature
  T_o = environmental temperature
  r = pool radius
  r_o = environmental radius
  dt = time increment
  L_f = latent heat of fusion.

Assuming $v_x = v_y = v_z$ and taking the pressure P on the area of beam impingement A from momentum considerations:

$$P = \frac{v_x}{A}\frac{dm}{dt} = \rho v_x^2 \ , \tag{8}$$

$$P \approx \frac{1}{\rho A^2} \left(\frac{IV - \frac{2\pi k w (T_m - T_o)}{ln\left(\frac{r}{r_o}\right)}}{L_f + \frac{3}{2}\frac{P}{\rho}} \right)^2 . \tag{9}$$

In the extremely unlikely event that the beam should be suddenly focused on an isothermal region all at the evaporation temperature, so that the local heat leakage is negligible, then an upper bound to the evaporation pressure can be obtained:

$$P \leq \frac{1}{\rho}\left(\frac{IV}{AL_f}\right)^2 . \tag{10}$$

For a beam power of 560 W acting over a 1-mm-diameter spot on pure aluminum (L_f = 69.6 kcal/g-mole, ρ = 2.70 g/cm^3) a tiny pressure of 16 dyn/cm^2 results.

If the power were an order of magnitude higher and the focal point an order of magnitude smaller, then pressures on the order of 0.2 atmospheres (1 atmosphere = 1.01×10^6 dyn/cm^2) might be achieved. This enters the regime of significant pressures and is consonant with an incident observed by one of the authors, wherein a sudden substantial sharpening of focus of a commercial EB welder penetrating a 1-in.-thick piece of 2219 aluminum blew out a substantial part of the weld pool.

With the Ukrainian UHT designed for space welding, it is not considered feasible for such conditions to occur, nor have any observations been made of apparent evaporation pressure effects with the UHT.

B. Wire-Related Detachments

1. Molten Metal Accumulations

As part of this inquiry the question must be asked whether the weld wire could be run into the electron beam in such a way as to create a massive accumulation of molten metal on the end of the wire, which could detach and present a threat to the EMU. A steady-state solution for the temperature along an infinite wire moving into a heat source exists. The power dissipated in the wire is $\rho CAV(T_e - T_o)$, where ρ is the density of the wire, C the specific heat, A the cross-sectional area of the wire, V the velocity of the wire, T_e the temperature at the heat source approached by the wire, and T_o the ambient temperature. A 1-mm-diameter aluminum wire heated to melting at the hot end dissipates approximately 23 W of power at the maximum (runaway) wire speed of 1.6 cm/sec with an ambient temperature of 20 °C. A similar iron wire dissipates 63 W. The increased dissipation is due to the higher melting temperature and density of the iron wire. The beam power for operation at 8 V and a typical 50 A is 400 W. The highest of the above estimated wire power dissipation is only 16 percent of beam power. This is why the beam cuts the wire. When a 400 W beam impinges on a segment of wire, each side extracts power, e.g., 126 W for the iron example cited above, but this leaves 274 W to power a transient temperature rise of the impingement site to melting and vaporization.

In addition to the not-very-large expenditure to maintain the melting temperature at the end of the wire, the phase transformation to melt (or vaporize) the wire requires power ρLAV, where L is the latent heat of the transformation. The aluminum melting transition requires around 14 W; iron, 27 W. Hence, the end of a runaway aluminum weld wire moving into a beam with an overall power of 37 W should melt into a blob. A bit more power will be required to overcome radiation losses. An iron wire should do the same for a 90 W beam.

But if the power level supplied by the UHT beam is certainly adequate to melt the wire, perhaps it is so high that vapor rather than molten metal will be the result. To vaporize the aluminum requires roughly an additional 380 W; to vaporize the iron, 670 W. Thus a 420 W beam should vaporize the aluminum wire even under runaway conditions if all the power goes into the wire. If the power capture cross section is only 50 percent of the total beam area, then 840 W would be required. At the slowest wire speed, with 100-percent beam power capture, only 290 W would vaporize the wire. The figures for iron are 760, 1,520, and 520 W, respectively.

It is to be concluded from the above figures that the beam power and wire velocity settings are in a range where melting and appreciable evaporation are to be expected. Under such conditions a large blob of liquid metal could form on the end of a runaway wire, particularly if only part of the full power of the beam encounters the wire. With highest power levels the wire may generate enough vapor to break up in the beam with associated sparking or even to vaporize completely. Hence, the condition thought most likely to generate large liquid metal blobs is that of minimum power and maximum wire speed.

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2. Flickout from the Pool

It is also conceivable that the weld wire could act as an instrument to detach molten metal by flicking it out of the weld pool if the wire end were to be suddenly whipped out of the puddle. Figure 6 illustrates a conceptualization of the "flickout" mechanism.
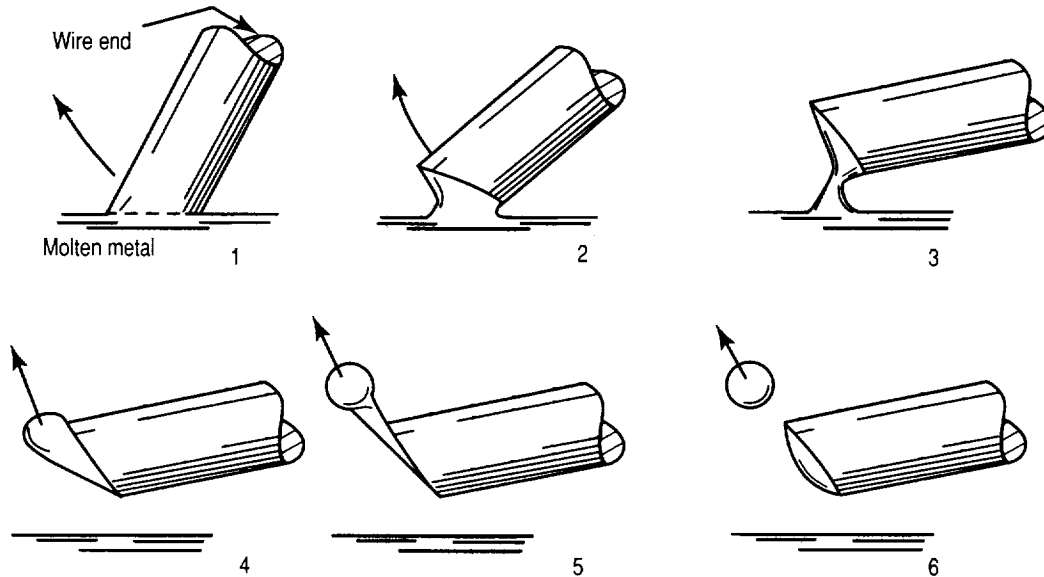
Figure 6. Flickout of molten metal from the weld pool.

As the wire end exits the pool, stage (1) of figure 6, it drags the surface of the pool along with it (2). The surface area increases until it becomes unstable (3), contracts at some region between pool and wire, and separates to leave a volume of molten metal attached to the wire (4). If a portion of the molten metal attached to the wire has enough kinetic energy to form a neck (5) behind it and to draw out the neck until separation takes place, the result is a free molten metal globule (6).

III. TEST RESULTS AND INTERPRETATION

A. Molten Metal Detachments

1. Weld Pool and Cut Detachments

Some initial attempts to produce detachments of drops of liquid metal on the edges of cuts were made, but the attempts were frustrated by gravity. The drops all formed on the bottom cut edge where they were caught and ran down the plate surface whether they were totally detached or whether they were merely detached from the upper surface to drip down the plate surface. Therefore, it was decided to restrict studies to weld pools rather than cut edges.

Values of the "weld pool detachment parameter" of equation (6) for full penetration welds are tabulated in table 1 with indications as to whether full detachment or partial detachment (dripping) occurred. "Full detachment" does not necessarily mean that the whole pool fully detached; in some cases only a smaller portion of the pool detached, the remainder dripping down the plate. "Partial detachment" means that the pool detached from one side of the liquid-solid boundary so as to leave a hole at the puddle site but remained attached over part of the liquid-solid boundary and dripped down the plate with no fully detached material detected.

The values come from tests of three plates—308L stainless steel, 2219 aluminum, and 5456 aluminum. Four welds and four associated hammer blows were made on each plate. The computed weld pool detachment parameters should be regarded as only rough approximations. Values used to compute the weld pool detachment parameters are presented in the appendix. The surface tensions were estimated from values for molten elements given in the *Handbook of Chemistry and Physics*.[3]

Table 1. Weld pool detachment parameters.

Parameter	Detachment Status	Material
0.6		308L
1.4	Partial detachment (dripping)	5456
1.6		5456
1.8	Partial detachment (dripping)	Ti–6Al–4V
2.3		308L
2.5	Full detachment	308L
3.5	Partial detachment (dripping)	2219
4.5	Full detachment	2219
4.5	Partial detachment (dripping)	308L
4.5	Full detachment	Ti–6Al–4V
4.7	Partial detachment (dripping)	5456
5.0	Full detachment	5456
7.1	Partial detachment (dripping)	Ti–6Al–4V
9.9	Partial detachment (dripping)	2219
10.7	Full detachment	Ti–6Al–4V
14.3	Full detachment	2219

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Table 1 shows full detachments beginning with a weld pool detachment parameter on the order of 2. This confirms equation (6), which requires the kinetic energy of the weld pool relative to its environment to be greater than the surface energy increase to detach the pool but does not say how much greater. It may be that the actual surface energy increase is larger than the rough estimate used here. It is likely that not all of the kinetic energy is available for detaching the pool; some may be sequestered in weld pool oscillations. The coefficient of restitution e for the collision will be lower than 1 (used in the computations) if irreversible deformation; for example, plastic flow deformation, takes place during the collision.

Whether detachments are full or partial is not distinguished. The complexity of details required for such a computation would be prohibitive. What is important in the present situation, however, is merely that the weld pool detachment parameter, according to theory and according to the empirical data above, allows a determination of whether full detachments might occur.

It was not particularly easy to generate the detachments for this experiment. Substantial hammer blows were struck. The specimen was suspended so as to be free to respond to the blows with a sudden velocity increment. In general, on-orbit detachments due to reasonably anticipated shocks are judged so unlikely as to be discounted.

The above theory is applicable to other hypothetical conditions as desired for assessing the potential for molten metal detachment.

B. Weld Wire Detachments

Wires (308L stainless steel, 2319 aluminum, and 5356 aluminum) were run into the beam used for welding the respective plates at a low speed of 1.08 cm/sec and a high (but not runaway) speed of 1.31 cm/sec. The wires melted and fell under the action of gravity. Any vapor effect, which would be masked by gravity in a direction perpendicular to the Earth's surface, would, it was thought, reveal itself in the trajectories of droplets parallel to the Earth's surface. Little parallel spread of the droplets from the wire was noticed for any material, and it was concluded that vaporization forces were negligible. Possibly, the beam profile only partially overlapped the wire so as to deliver only a portion of total power to the wire.

Given the small volume of molten metal entrained on the weld wire and the difficulty of producing sudden wire movements in the cramped configuration in front of the UHT in the experimental vacuum chamber, it is not surprising that experimental attempts to produce free molten metal drops by wire "flickout" were unsuccessful.

It appears possible that wire positioned to enter the beam could form a large blob of molten metal at a rate of 12.6 mm^3/sec with a 1-mm-diameter wire at a wire runaway speed of 1.6 cm/sec. The drop diameter d would grow with time t according to the relation $d^3 = 24t$. Thus, after 1 sec the drop would be 2.9 mm in diameter; 2 sec, 3.6 mm; 5 sec, 4.9 mm; 10 sec, 6.2 mm; and 100 sec, 13.4 mm.

If the wire should move into the beam in the above fashion, an appropriate countermove is to touch the growing drop to the weld sample so as to provide a path for the heat to exit and allow the drop

to solidify and subsequently to allow the wire to be bent out of the path of the beam. A 1-mm-diameter connection to the drop with a surface tension of ~ 1000 dyn/cm would tolerate a lateral force something on the order of 100 dyn or 0.0033 oz. This level of force would be generated in accelerating a drop of 1 g (for example a 9-mm-diameter drop of aluminum) at 1 m/sec^2 or about 1/10 terrestrial gravity. This would presumably be a feasible movement. And if the drop should break away, it acquires a velocity towards the sample plate by the impulse from the attempt to move it.

IV. CONCLUSIONS AND RECOMMENDATIONS

A parameter indicating whether or not a weld pool detachment will occur under specific welding/impact conditions has been derived and its predictions agree with test data.

According to theory, the likelihood of metal detachments is proportional to the weld metal density and the weld pool radius and inversely proportional to the surface tension of the molten weld metal. For the same size weld pool, theory estimates metal detachment to be most likely for the 308L stainless steel and least likely for the Ti–6Al–4V.

Molten metal detachments from the weld pool or from the edges of a cut are considered extremely unlikely to occur due to anticipated acceleration g-forces or impacts or vapor reaction forces of the electron beam in the space environment.

Molten metal detachments from the weld wire can occur if the weld wire runs unchecked into the beam, but this can be countered by moving the wire end with the drop attached to touch the sample plate. If the wire were to run away into the beam (mechanical failure) and the operator were not to notice this for 10 sec (operator inattentiveness), and then the operator were to jerk the UHT back suddenly so as to detach the drop and give it an impulse towards the EMU (improper operational procedure) and at the same time to move the welder aside to open a path for the drop to strike the EMU, it is possible that a 6-mm-diameter drop could impinge on the EMU. Even in this highly unlikely situation the result would not necessarily be disastrous because vapor from the teflon outer fabric of the EMU would repel the drop, but the reaction of the EMU fabric to liquid metal impingement is the subject of another study.

This study concludes that molten metal detachments during electron beam welding in the space environment do not present a credible hazard.

The conclusions established here for electron beam welding are applicable to other potential space welding processes that produce similar weld geometries, with one exception. For any process involving emission of a gas (e.g., plasma arc processes) or producing high magnetic fields or in some other way exerting forces on the weld pool other than the impulse reaction of the evaporated metal considered here, it will be necessary to assess the level of these forces and their effect on possible liquid metal expulsion.

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APPENDIX

EVALUATION OF WELD POOL DETACHMENT PARAMETER

Refer to equation (6) and figure 5 in text above.

General parameters:

g = acceleration of gravity = 980.6 cm/sec^2

M = mass of striker = 1,650 g

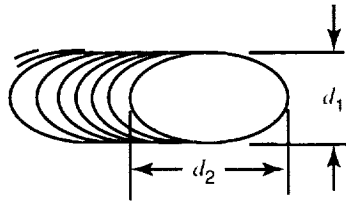L_R = impact location distance from sample pivot = 23.8 cm.

Figure 7. Weld pool dimensions.

Note 1. The weld pool "radius" r for an irregular pool approximated as an elliptical pool of axes d_1 and d_2 is computed from the relation:

$$r = \frac{\sqrt{d_1 d_2}}{2} \quad . \tag{11}$$

If the pool shape is circular, then:

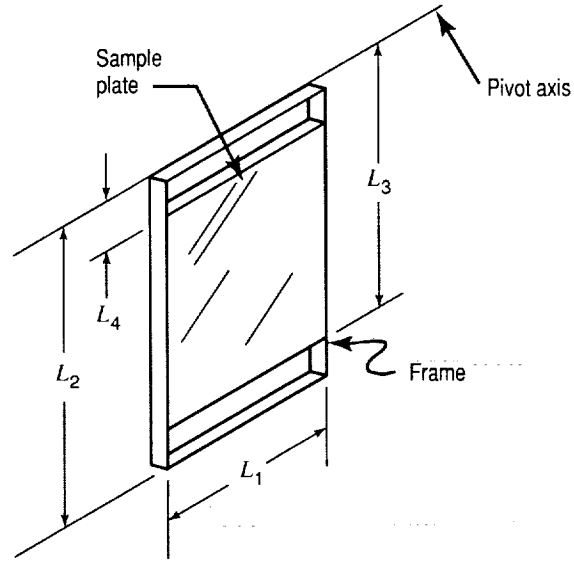$$r = \frac{\sqrt{(2r)(2r)}}{2} = \frac{2r}{2} = r \quad . \tag{12}$$

Figure 8. Weld sample in pivoted frame.

Note 2. The effective length L of the sample plate is computed from the relation:

$$\frac{1}{3}mL^2 = \frac{1}{3}\left[\frac{2L_1 + 3L_2}{2L_1 + 2L_2}m_F\right][L_2]^2 + \frac{1}{3}m_s\left[L_3^2 - L_4^2\right] \quad , \tag{13}$$

where $m = m_F + m_s$

m_F = mass of frame = 1,042 g

m_s = sample mass

L_1 = frame width = 30.5 cm

L_2 = frame length = 35.7 cm

L_3 = pivot to plate bottom distance

L_4 = pivot to plate top distance.

Table 2. Weld plate parameters.

	308L Stainless	Ti–6Al–4V	2219 Aluminum	5456 Aluminum
m_s	852 g	332	378	422
m	1,894 g	1,374	1,420	1,464
L_3	27.9 cm	27.9	27.6	25.4
L_4	2.5 cm	5.1	4.8	2.5
L	35.2 cm	37.5	37.2	36.6

For computation of the weld pool detachment parameter:

g = acceleration of gravity = 980.6 cm/sec^2

e = coefficient of restitution for collision = 1 (i.e., collision assumed elastic)

L_R = pivot to impact site distance = 23.8 cm

M = striker mass = 1,650 g

L = effective length of sample/sample holder pendulum

m = target mass (sample plus frame)

ρ = density of molten metal

γ = surface tension of molten metal

h = striker drop distance

r = weld pool radius

x = pivot to weld pool distance.

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Table 3. Computation of weld pool detachment parameter.

$$\frac{\rho g h r}{4\gamma}\left(\frac{x}{L_R}\right)^2\left[\frac{1+e}{1+\frac{1}{3}\left(\frac{L}{L_R}\right)^2\frac{m}{M}}\right]^2$$

	h (cm)	x (cm)	d_1 (cm)	d_2 (cm)	r (cm)	Parameter
<u>308L Stainless</u>						
ρ=8 g/cm^3	5.1	12.8	0.4	1.0	0.32	0.6
γ=1,800 dyn/cm	10.2	13.2	1.0	1.5	0.61	2.5
m=1,894 g	15.2	13.1	0.8	1.2	0.49	2.3
L=35.2 cm	20.3	13.3	1.0	1.2	0.55	4.5
<u>Ti–6Al–4V</u>						
ρ=4.43 g/cm^3	5.1	22.8	0.4	0.7	0.27	1.8
γ=1,500 dyn/cm	10.2	24.3	0.4	0.9	0.30	4.5
m=1,374 g	15.2	24.3	0.4	1.0	0.32	7.1
L=37.5 cm	20.3	24.3	0.5	1.0	0.35	10.7
<u>2219 Al</u>						
ρ=2.83 g/cm^3	5.1	23.8	1.0	1.7	0.65	3.5
γ=900 dyn/cm	10.2	19.6	1.0	1.5	0.61	4.5
m=1,420 g	15.2	22.2	1.1	1.8	0.70	9.9
L=37.2 cm	20.3	22.8	1.1	1.9	0.72	14.3
<u>5456 Al</u>						
ρ=2.66 g/cm^3	5.1	24.2	0.4	0.7	0.26	1.4
γ=900 dyn/cm	10.2	21.8	0.3	0.5	0.19	1.6
m=1,464 g	15.2	20.8	0.7	0.9	0.40	4.7
L=36.6 cm	20.3	20.8	0.4	1.0	0.32	5.0

APPROVAL

AN ASSESSMENT OF MOLTEN METAL DETACHMENT HAZARDS FOR ELECTRON BEAM WELDING IN THE SPACE ENVIRONMENT: ANALYSIS AND TEST RESULTS

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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Conditions under which molten metal detachments might occur in a space welding environment are analyzed. A weld pool detachment parameter specifying conditions for pool detachment by impact is derived and corroborated by experimental evidence. Impact detachment for the pool is unlikely. Impact detachment for a drop of metal on the end of the weld wire may be possible under extreme conditions. Other potential causes of molten metal detachment considered, vaporization pressure forces and wire flickout from the pool, did not appear to present significant detachment threats.

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